Rheology of magnetic fiber suspensions

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RHEOLOGY OF MAGNETIC FIBER SUSPENSIONS

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This work reports the experimental and theoretical results on the steady-state shear flow of the suspension of magnetic fibers in the presence of a homogeneous magnetic field perpendicular to the flow. In experiments, we did not observe a significant static yield stress. However, the experimental flow curves show a steep initial section corresponding to gap-spanning aggregates formed in the fiber suspension under a magnetic field. At higher Mason numbers, aggregates are not more confined by the walls and the flow curves become linear manifesting a Bingham behavior with the dynamic yield stress growing with the magnetic field intensity. This yield stress for the fiber suspension appears to be about three times the yield stress for the suspension of spherical particles. Such difference is explained in terms of the enhanced magnetization of the aggregates composed of fibers compared to the aggregates composed of spherical particles.

1. Introduction

Magnetorheological (MR) fluids belong to a class of smart materials, which mechanical properties can be tuned by means of external magnetic fields. A liquid-to-solid transition and appearance of a significant yield stress in these fluids upon application of a magnetic field is referred to as a magnetorheological effect. This effect has found industrial applications in active damping systems and in finishing of optical surfaces [1,2]. Nowadays, sedimentation of MR particles and reduced lifetime of the existing MR fluids are the major problems affecting the performance of the MR smart devices. Ngatu et al. [3] has proposed to use elongated magnetic particles together with spherical ones in order to improve the sedimentation stability of the MR fluids. Besides the sedimentation stability, the MR fluids based on rod-like magnetic particles experience a few times higher MR effect as compared to conventional MR fluids composed of spherical particles. Methods of synthesis of magnetic rod-like particles, their characterization and MR behavior of the suspensions based on these particles are reported in papers by Bell et. al [4,5], Vereda et al. [6], de Vicente et al. [7], Lopez-Lopez et al. [8,9], Gomez-Ramirez et al. [10]. An enhanced MR effect observed in magnetic fiber suspensions has been recently explained by either solid friction between fibers [11] or by enhanced dipolar interactions between them [7]. In this paper, we present new experimental results on the steady shear flows of fiber suspensions under a magnetic field and develop a new micromechanical model of these suspensions taking into account both magnetic and hydrodynamic interactions.

2. Experiments

The MR fluids used are composed of cobalt micro-fibers dispersed in silicon oil of a viscosity η_0=0.479 Pa·s at a volume fraction of Φ=5%. The fibers were synthesized by a reduction of the cobalt ions in polyol liquid in the presence of an external magnetic field [8]. The fiber morphology is shown on optical microscopy pictures in Fig. 1a. The fibers are rather polydisperse and are aggregated into small flocks while dispersed in a silicon oil. Their mean length and diameter are $2l$=37 and $2a$=4.9 μm, respectively. So the mean fiber aspect ratio is l/a=7.6. The magnetization curve was fitted to a Fröhlich-Kennelly law: $M=\chi_i M_S H/(M_S+\chi_i H)$, with χ_i=70 – initial magnetic susceptibility of fibers and M_S=1366±8 kA/m – the saturation magnetization.

The flow curves of the fiber suspensions were measured using a Haake RS150 control stress rheometer in a plate-plate geometry, with the plate diameter being 35 mm and the gap between plates 0.2 mm. A homogeneous magnetic field of intensity H_0, ranging from 0 to 30.6 kA/m, was generated by using a specially designed solenoid. A stress cycle was applied to the suspensions: first, a growing stepwise stress ramp was applied from 0.1 Pa to some maximum value depending on the magnetic field intensity; then, the same procedure was repeated but decreasing the stress. The measurements at increasing and decreasing shear stress were carried out in order to check the possible hysteresis of the flow curves, which could be a manifestation of the solid friction between fibers.

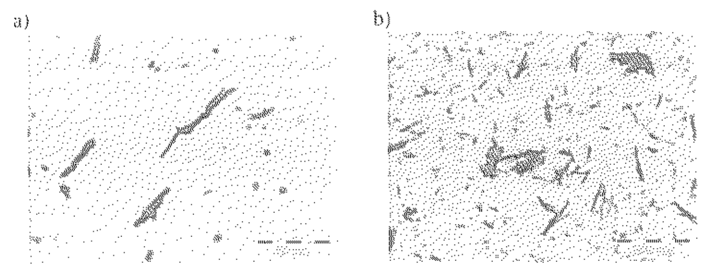

Figure 1. Optical microscopy images of the magnetic fibers in a silicon oil. Figure (a) shows fiber's morphology and figure (b) - fiber's polydispersity and formation of flocks under colloidal forces.

The experimental flow curves of the fiber suspension are shown in Fig. 2 for different magnetic field intensities. We see that the flow curves have two straight sections with different slopes, the left one with a steep slope and the right one with a less steep slope. The steepness of the initial part of the flow curve is likely due to the presence of the gap-spanning aggregates, which offer a high hydraulic resistance to the flow. The small-slope section of the flow curve corresponds to the shear rates $\dot{\gamma}$>50 s^{-1} and is attributed to the regime of free aggregates not touching the walls and oriented close to the direction of streamlines. At this regime, flow curves are linear and almost parallel to each other, which corresponds to the Bingham rheological law, $\tau = \tau_y + \eta\dot{\gamma}$, with τ_y being the dynamic yield stress and η the plastic viscosity. The rounded part of the flow curves corresponds to the transition between the regime of confined aggregates to that of free aggregates.

In experiments, we observe a relatively small static yield stress – the real threshold stress at zero shear rate, corresponding to the failure of the suspension structure and to the flow onset. It is, at least, one order of magnitude lower than the dynamic yield stress. The smallness of the static yield stress could be understood by a poor adhesion of the aggregates to the rheometer plates, made of titanium with a roughness around 1 micron. So, when the suspension is sheared, the aggregates are supposed to slide on the plates with only a low solid friction, which probably gives a negligible contribution to the shear stress.

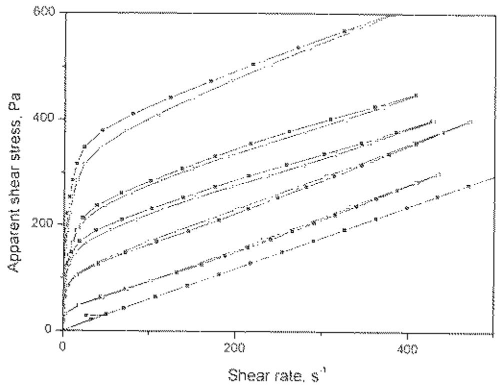

Figure 2. Flow curves of the suspension of magnetic fibers under magnetic fields of different intensities: from bottom – to top curve: H_0=0, 6.11, 12.2; 18.3; 24.4 and 30.6 kA/m. Full and open symbols stand respectively for increasing and decreasing magnetic fields.

Notice finally, that the experimental flow curves have a small hysteresis, which could come from the solid friction between fibers. Nevertheless, the smallness of this hysteresis could mean that the hydrodynamic forces dominate over the forces of solid friction.

3. Theory

To predict the dynamic yield stress developed in the fiber suspension under a magnetic field, we adapt the model of drop-like aggregates developed by Shulman et al. [12] for a conventional MR fluid to the suspension of rod-like particles. The principal hypotheses of this model are as follows. Under the action of an external magnetic field, the fibers are supposed to form drop-like aggregates with high aspect ratio. These aggregates are displaced with the shear flow; they do not rotate but are inclined by the hydrodynamic torque. The angle θ of their inclination with respect to the field direction is defined by the balance between magnetic and hydrodynamic torques. The aggregates are also subjected to a tensile hydrodynamic force trying to break them but the magnetic attractive

forces between particles consolidate the aggregate such that its size (or rather aspect ratio, r) is defined by the balance between these forces. We use Ginder's model [13] for calculation of magnetic interactions between closely spaced particles with high magnetic permeability. Once the microstructural parameters, θ and r, are obtained, we calculate the shear stress generated in the suspension by using Batchelor's slender body theory [14] adapted to the case of particulate system with external torques [15]. The shear stress is the sum of the solvent stress, $\eta_0\dot{\gamma}$ and of the particle stress. The latter is roughly proportional to $\eta_0\dot{\gamma}r^2$, and since $r^2 \propto \dot{\gamma}^{-1}$, the particle stress appears to be independent of the shear rate. So, the particle stress is associated to the dynamic yield stress, τ_y. In experiments this stress is defined by an extrapolation of the linear part of the flow curve onto the zero shear rate. The final result for the yield stress reads:

$$\tau_y = \Phi\mu_0 H^2\left\{\left(\frac{2M_S}{3H}\frac{\chi_f^{\,2}(1-\Phi)}{2+\chi_f(1-\Phi)}\right)^{1/2}\sin^2\theta\cos^2\theta + \frac{\chi_f^{\,2}(1-\Phi)}{2+\chi_f(1-\Phi)}\sin\theta\cos^3\theta\right\}, \qquad (1)$$

where μ_0 is the magnetic permeability of free space, H is the internal magnetic field, χ_f is the magnetic susceptibility of fibers.

In order to compare the MR effect of fiber suspensions with the one of suspensions composed of spherical particles, we adapt our model to the suspension of spheres and obtain the same expression (1), in which Φ must be replaced by Φ/Φ_a and χ_f by χ_a, with Φ_a≈0.64 – the internal volume fraction of aggregates of spherical particles and χ_a is the magnetic susceptibility of these aggregates.

The field dependence of the yield stress of both kinds of MR fluids is presented in Fig. 3. Both in experiments and in theory, we observe a few times enhancement of the yield stress in fiber suspensions as compared to the suspension of spheres at the same volume fraction. Such difference is explained in terms of higher magnetization of aggregates composed of fibers compared to aggregates composed of spheres. In fact, the demagnetization field is lower in aggregates composed of aligned fibers, so the magnetization of these aggregates is higher.

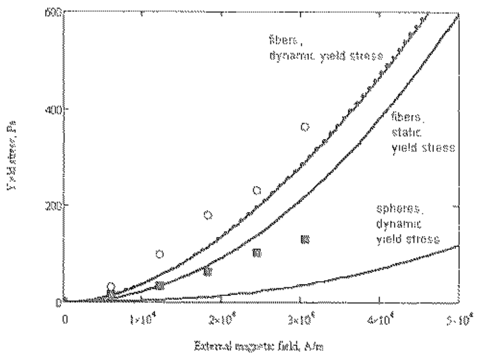

Figure 3. Yield stress of the suspensions of magnetic fibers and of magnetic spheres as function of the intensity of an external magnetic field. Circles and squares stand for experimental results on fibers and spherical particles, respectively; lines correspond to the theory.

In Fig. 3, we see that the theory predicts reasonably well the yield stress in fiber suspensions but underestimates it significantly in suspensions of spherical particles. This is likely because our model underestimates magnetic interactions between spherical particles.

We have also plotted in Fig. 3, the theoretical curve corresponding to the static yield stress in fiber suspensions. This quantity was calculated using our previous model [11], in which we considered a quasi-static deformation of the fiber suspension and took into account a solid friction between fibers characterized by a friction coefficient ξ, which is of the order of unity. Interestingly, this model gives a rather close result on the yield stress compared to the model presented in this paper, even though both theories are based on completely different grounds.

4. Conclusions

In this study, we have confirmed the enhanced MR effect generated in suspensions of rod-like particles, compared to those of spherical magnetic particles, which is attributed to a stronger magnetization of aggregates composed

of rod-like particles. The flow curves of the fiber suspension have two linear sections with different slopes. The initial steep-slope section corresponds to the gap-spanning aggregates and the final small-slope section does to smaller aggregates almost aligned with the flow. We have developed a theoretical model predicting a dynamic yield stress in fiber suspensions taking into account hydrodynamic interactions. This model gives a reasonably good correspondence with experimental results.

Acknowledgments

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